Fourier Optics

Swarthmore College

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Report
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Acknowledgments

This report is the final product of a long, challenging process. As such, it would not have been possible without the help of many people. First and foremost, I would like to thank my professor and mentor Professor Lynne Molter for her guidance throughout this project and for providing me with some excellent advice during our meetings. I would also like to thank her for her patience when I kept asking questions that she had already answered several times over.

I would like to take this opportunity to thank Swarthmore Collge Engineering Department for giving us the opportunity to work on such a brilliant idea and also for providing us with all the essential facilities to carry out our project smoothly.

Finally, I would like to thank my parents who always encouraged me and never let me give up on my dreams even when things were tough. They have always been there for me through thick and thin, and have given me the confidence to pursue what I want in life. I take this opportunity to express gratitude towards all those people who directly or indirectly helped me in the completion of this report.

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Abstract

Fourier analysis is a key tool in physics and engineering in the broadest sense and is particularly used in the field of optics to design and study the properties of advanced imaging systems. For my E90 final project, I intend to explore areas describing a simple experimental setup that illustrates the spatial frequency-domain response of a simple optical system. This experiment clearly demonstrates spatial transfer function concepts in Fourier optics, complementing and extending other studies of Fourier transforms in physics that may consider similar ideas in a time and frequency signal-processing context. Future applications include the optical data processor or optical computer. The basis of spatial filtering is Fraunhofer diffraction from the object whose image is to be spatially filtered.

Introduction

2.1 Background Information

With the rapidly increasing importance of advanced imaging techniques in physics and technology, Fourier optics is widely recognized as an essential background for any optics engineer or student in physics. The basic concepts of Fourier optics applied to imaging date back to the 1940s, first introduced by Duffieux and then extended by many others. The origins of Fourier Optics date back to the seminal work of James Clerk Maxwell in the 1860s on wave propagation through periodic media – known today as dispersive wave phenomena. The term "Fourier optics" was coined by Lippmann in 1933 while attempting to apply Fourier analysis methods to problems involving light diffraction through gratings.

Fourier optics is a branch of optics that deals with the study of optical systems. It includes the theory and practice of imaging, interferometry, diffraction by gratings, and fiber optics. Fourier optics also refers to methods for decomposing any waveform in terms of sinusoidal components which may then be processed using standard techniques in Fourier theory. The field is named after Joseph Fourier (1768-1830), who showed that any periodic function can be represented as a weighted sum of trigonometric functions.

Fourier optics provides a unified framework for describing and analyzing systems that manipulate or process optical signals. Fourier optics is relevant to a broad range of diverse fields, including signal processing, image processing, optical imaging and communications; data storage; pattern recognition (optical information processing); holography; diffractive optics; lens design; wavefront sensing, and correction. It is built based on the Fourier transform, which is a mathematical operation that converts an object (e.g., an image) into its frequency spectrum. The

Fourier transform can be used to convert an optical signal from one domain, such as space or time, into another domain (space and time).

Fourier Optics or Optical Fourier Transform (OFT) is an important part of image processing because it allows us to separate the different light waves into their individual frequencies or waveforms so we can see all these components separately which means we can enhance/change them individually rather than just adjusting everything at once like increasing contrast etc. This makes things much easier because you don't have to worry about messing up some other area when trying something new out! Fourier analysis is also used to find out how much of each frequency component contributes to an image's intensity distribution in space. A typical application would be to use a diffraction grating or lenslet array in combination with an infrared camera to measure microscopic features such as cracks on aircraft wings or defects on semiconductor wafers.

2.2 Project Objectives & Goals

Students are often exposed to important mathematical concepts that can be difficult to understand because they’re not intuitive or presented using practical applications. Fourier Transformation is a mathematical topic frequently taught in advanced courses of study. Explanations of this important concept are usually supplemented with graphical aids such as waveforms and plots showing the distribution of energy vs. frequency, etc. These can help students grasp what can be done with Fourier Transforms from a mathematical point of view in what could be considered a virtual presentation form. But most people relate to and become more excited about real-world results and that is where laboratory studies can be beneficial.

In this experiment, the goal is to examine the fundamentals of spatial filtering in Optical image processing. Spatial filtering beautifully demonstrates the technique of Fourier transform optical processing, which has many current applications, including the enhancement of photographic images and television pictures. Future applications include the optical data processor or optical computer. The basis of spatial filtering is Fraunhofer diffraction from the object whose image is to be spatially filtered.

Theory

3.1 Fourier transform

The Fourier transform is a tool for analyzing time-dependent phenomena. It converts a signal from the time domain to the frequency domain and vice versa, which means that it can be used to analyze both how a signal changes with time and how its amplitude varies with frequency. In other words, if you have some data about what happens over time and you want to know what it looks like in terms of frequencies or vice versa, the Fourier transform is what does this job for you.

$$y(f) = \int_{-\infty}^{+\infty} y(x) \times e^{-i2\pi f x}\, dx \quad \Leftrightarrow \quad y(x) = \int_{-\infty}^{+\infty} y(f) \times e^{i2\pi f x}\, df$$

Figure 1. A mathematical expression of Fourier transforms that transforms a function of time, y(t), to a function of frequency, Y(ω).

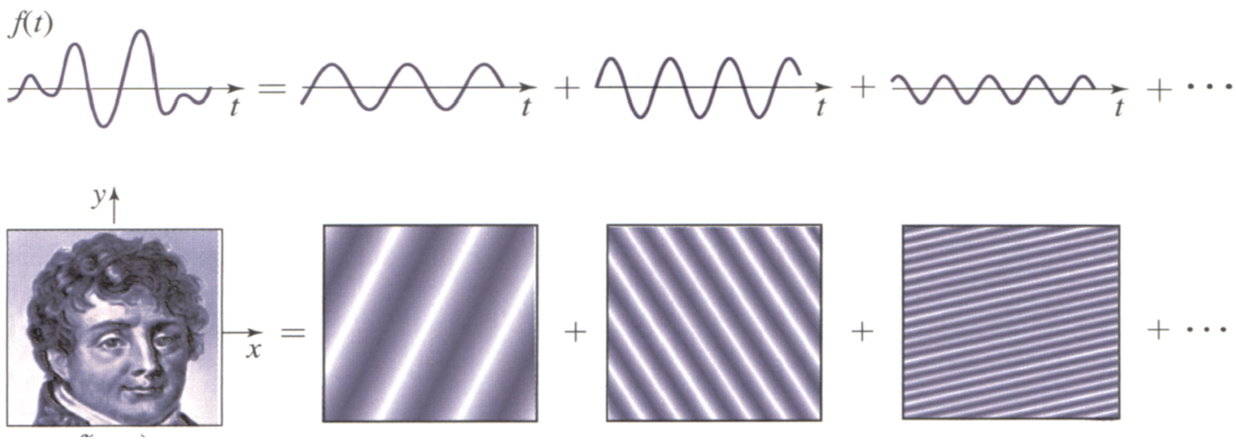
Mathematically, Fourier's theory asserts that all functions can be expressed in terms of sine and cosine functions with different amplitudes and frequencies. The Fourier transform of a function is like a continuous frequency spectrum of a signal, where each frequency's importance is weighed by their respective amplitudes. Squaring a Fourier transform gives an intensity distribution. Thus, a squared Fourier transform gives the intensity distribution of an image's diffraction pattern because, as you will see later, a diffraction pattern divides an optical signal into spatial frequencies and "weighs" their importance with an intensity distribution. Using Euler’s formula for harmonics motion we can show how a function can be made up of a sum of sinusoidal functions.

$$e^{ix} = \cos x + i \sin x$$
$$e^{-ix} = \cos x - i \sin x$$

Figure 2: Euler Method formula

These are given to show that it is plausible that general waveforms can be considered as a sum of sines and cosines. Note: as you add sinusoid waves of increasingly higher frequency, the approximation gets better and better.

This will lead us to conclude that any waveform, image, etc.. can be expressed as the superposition of numerous harmonics…the more harmonics you are willing to have, the closer the representation of the original waveform/image.



http://faculty.washington.edu/lylin/EE485W04/Ch4.pdf

Figure 3: Representation of an image using Fourier transform

3.1.1 Properties of Fourier Transforms

Fourier transforms have many useful properties. The most important ones are

Linearity: Convolution is the product of two transform operations, and the result is always a linear function of its arguments. This means that if you have a Fourier transform of a function f(x), and another function g(x), then their convolution has a Fourier transform equal to their product (f * g).

Scaling: If you multiply your data by an arbitrary constant C, then multiplying it back again will return exactly what you started with (C times the original data). In other words, scaling doesn't change the shape of your data; it only changes its size by whatever factor C may be. The same property holds true for addition or subtraction as well--you can add multiple copies of your original signal together or subtract them from one another without changing anything about their shapes or behavior in any significant way.

Time-shifting: You can shift/spread/scale your signal forward in time using multiplication by sine waves with different frequencies (ω1,...,ωn) and phases (φ1,...,φn). This lets us look at signals whose frequency components are not evenly spaced throughout all time periods (e.g., looking at high-frequency components over short intervals).

Fourier transforms have many applications. The Fourier transform is used in signal processing, image processing, data compression, digital filters, and communication theory. Some applications for the Fourier transforms include

- Analysis of signals to look for features such as a particular set of frequencies. By simple pattern matching of frequency amplitudes and/or phases, recognition of voice or image content is possible.
- Implement filtering operations such as high pass, bandpass, low pass, matched filtering, etc. Convolution in the signal domain is equivalent to multiplication in the frequency domain so once a filter (convolution) Kernal exceeds a certain size, transforming into the frequency domain, multiplying, and transforming back is more efficient than performing a large convolution directly

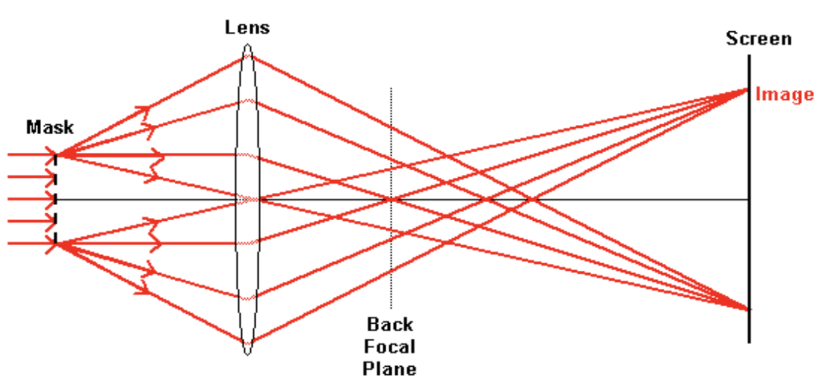
A complete description of the imaging system requires the wave properties of light and associated processes like diffraction to be included. It is these processes that determine the resolution of optical devices, the image contrast, and the effect of spatial filters. The study of classical optics using Fourier transforms (FTs), in which the waveform being considered is regarded as made up of a combination, or superposition, of plane waves. This is referred to as Fourier Optics.

3.2 Diffraction

Diffraction patterns are something we can observe that confirms the wave behavior of light. We don't witness light wave behavior often in daily circumstances unless we're treated to a rainbow or see the visual effect of a thin oil film on water. But artificial conditions can be set up that dramatically demonstrate the wave nature of light, as you'll see in this activity.

Diffraction patterns result from constructive and destructive interference when a solid object blocks coherent, collimated, monochromatic light. The edge of the solid object generates a new wavefront that eventually combines with the original unobstructed light wave. Since the wavefronts travel different path lengths they can add or subtract at various points away from the object edge, much like two ripples converging in a pond. From a practical point of view, the laser and spatial filter setup in my experiment meet the criteria of "coherent, collimated, and monochromatic

Diffraction is most simply defined as the bending of light around obstacles, or more accurately, diffraction is the Fourier transform of an image.



https://laser.physics.sunysb.edu/_lidiya/report/index.html

Figure 4: Diffraction is the Fourier transform of an image

When collimated light illuminates an object (consider a Ronchi grating for simplicity), light passes through the transparent portions of the grating un diffracted. The edges of the grating bend the light at certain angles to form a diffraction pattern (without a lens). The center of the diffraction pattern contains unbent collimated light. The light that is bent, forms maxima located at a certain distance away from the middle maximum. These maxima are diffraction orders. A lens "focuses" this diffraction pattern at its focus (Fourier plane). Actually, the unbent light that passes through the grating is focused at the focus of the lens because it is collimated light. The bent light comes to the lens at an angle, and thus the lens helps bend it even further away from the un diffracted light maximum focused in the middle of the pattern. So this is how diffraction maxima are formed at the focal plane of the lens. The lens simply "maps" and enhances how much the light diffracts around the object (it sorts the light into diffraction orders at its focus).

Diffraction patterns observed at a distance close to the object have a different visual appearance than those viewed at large distances. The close or finite case is termed Fresnel or near-field diffraction. Fraunhofer or far-field diffraction is the term for patterns viewed at large distances or infinity.

3.2.1 Fraunhofer diffraction

A lens is usually used to create a pattern called Fraunhofer diffraction in its focal plane. The Fraunhofer diffraction is also referred to as far-field diffraction. It is a classification of diffraction effects that arises from the type of mathematical approximations possible in order to compute the resulting diffraction patterns. In particular, we consider diffraction caused by a coherent light producing a final pattern on a screen placed effectively far enough that the incoming wavefront of light is plane.

Note: The size of the diffraction pattern is proportional to the distance from the lens to the Fourier Transform plane. It also depends on having a collimated beam of light, one whose rays are parallel and whose diameter remains constant over distance.

Methods

4.1 Basic Setup for Simple Fourier Optics Experiments

The resources I need for this project are available both in the Swarthmore Lab and Other theoretical materials needed for this project are freely accessible on Google and other data databases including textbooks.

The physical materials I need for my experimental setup include Spatial Light Modulator (SLM), laser(1-15 mW (or larger) red (633 nm) linearly polarized single spatial mode (TEM00) HeNe laser), Expanding lens, Collimating lens, Object plane spatial light modulator (O-SLM), Object lens (OL), Filter plane spatial light modulator (F-SLM), Image lens (IL), Image lens (IL), Image plane screen (S) and CCD camera.

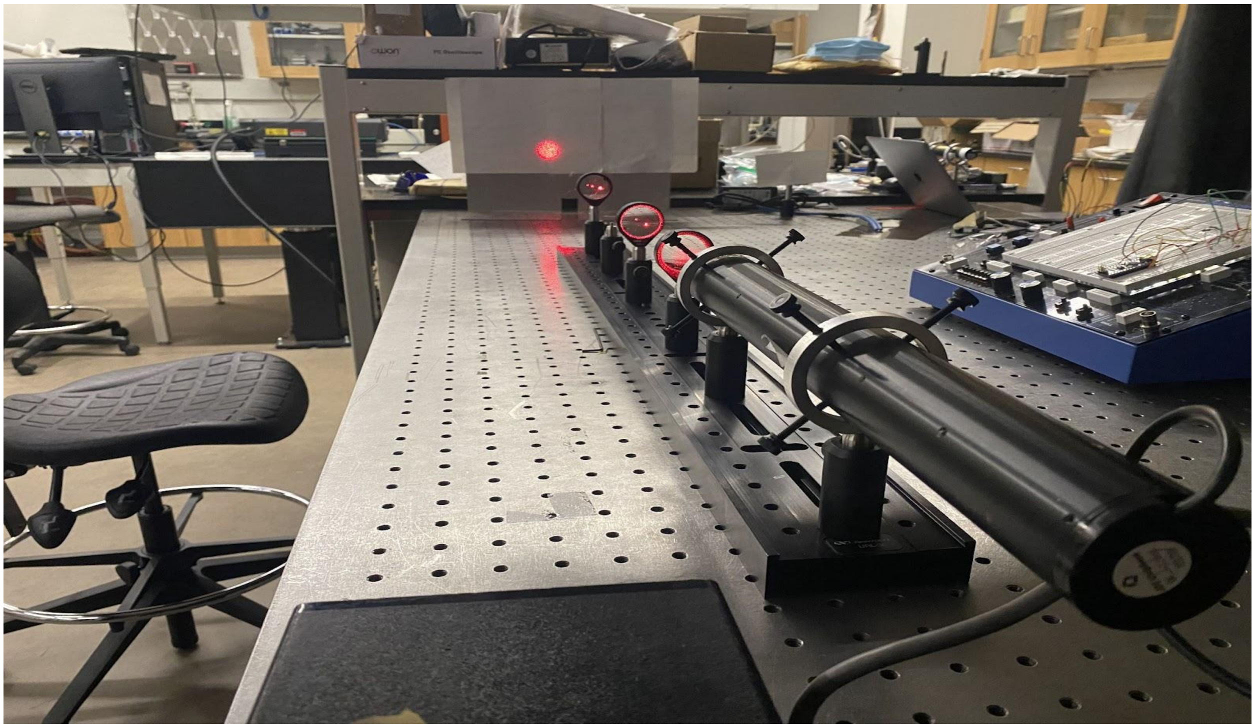


Figure 5: This is an image of the basic setup for Simple Fourier Optics Experiments

- **Laser**: 1-15 mW (or larger) red (633 nm) linearly polarized single spatial mode (TEM00) HeNe laser. Typical beam diameter of 0.5 to 1 mm. A lower power laser can certainly be used but once the beam is expanded, brightness will be greatly reduced. Even with the higher power laser, it will still not be exactly "bright". Note that in terms of eye safety, once the beam is expanded, the risk goes way way down because (1) it is no longer collimated and thus will not focus to a point on the eye's retina, and (2) the power density will have dropped by a huge amount at any realistic distance from the laser. Installing the expanding lens directly on the output bezel of the laser can assure that the original narrow beam is never present.
    - The beam from the laser must be linearly polarized to be usable with the SLM. (This is not a requirement for basic Fourier Optics experiments using only lenses and film slides or other patterns.) A polarized beam is most easily provided by a

linearly polarized HeNe laser. But a similar result can be achieved by adding a linear polarizer in the beam path of a randomly polarized laser oriented at 45 degrees to the principle polarization axes of the laser. But this would cut the usable power from the laser by at least 50 percent.

Note: FL - Focusing Lens is a short focal length convex lens. It can be a simple lens, microscope objective, microscope or telescope eyepiece, etc. The focal length should be quite short - at most 1/4"

- **Expanding lens (EL)**: -4 mm FL DCV or 4 mm FL DCX glass AR-coated lens for lasers with a ~1 mm beam diameter; -2 mm FL DCV or 2 mm DCX glass AR-coated lens for lasers with a ~0.5 mm diameter beam.
    - A spatial filter consisting of a positive expanding lens and precision pinhole aperture located at its focus may be required to clean up the beam (not shown). This is needed to 'clean up the laser beam. The smaller the better as long as it can be positioned the beam's focus to pass through it. This is one place where a precision X-Y stage is highly desirable since the best pinholes are only a few um in diameter! (You can make the pinhole easily enough by using a pin through aluminum foil against a sheet of glass).

Figure 6. A movable circular pinhole

- **Collimating lens (CL)**: is a medium focal length convex lens with focal length F2 positioned to produce a parallel beam. Its diameter will determine the size of the transparency, transform place filter, and output images. Larger is better but will reduce the brightness for viewing the transform and output images.
  - The ratio of F1/F2 should be roughly the same as the ratio of the diameters of the useful aperture of CL (desired diameter of the field of view) to the HeNe beam.
  - 200 mm FL 50 mm diameter DCX AR-coated lens. Assumes a beam diameter of 1 mm; for other sizes, adjust the focal length so that the resulting diameter of the usable portion of the beam is approximately 35 mm (25 mm x 1.4). T
- **Object plane spatial light modulator** (O-SLM): O-SLM is placed in the collimated beam but the exact location is not critical.
- **Object lens (OL):** 150 mm FL (OL-FL) 50 mm diameter DCX AR-coated lens. The OL is placed exactly 1 OL-FL from the O-SLM.
- **Image lens (IL)**: 150 mm FL (IL-FL) 50 mm diameter DCX AR-coated lens. The IL is placed exactly 1 IL-FL from the F-SLM.

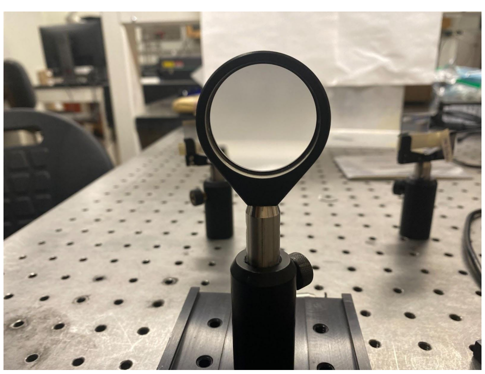
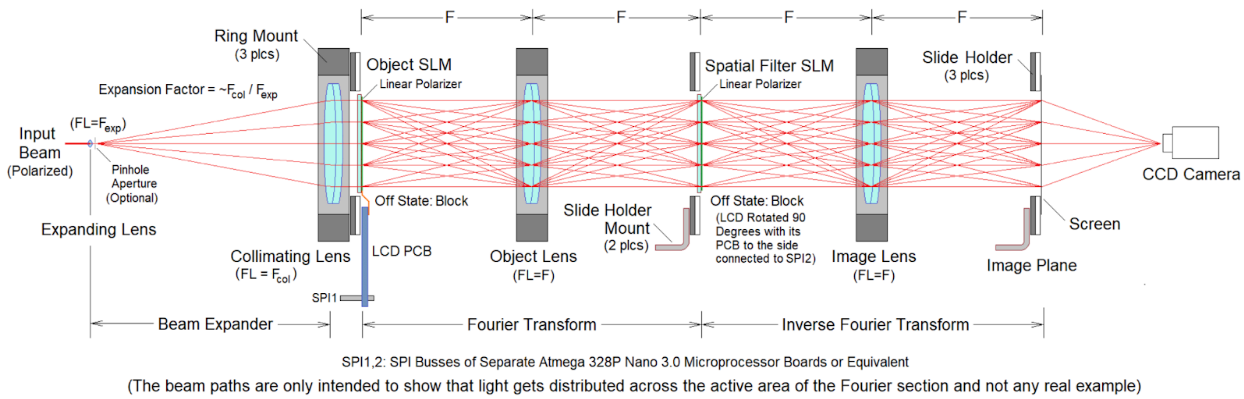


Figure 7. Image and object lens

- **Image plane screen (S)**: Piece of white paper.

Setting up and aligning the optical components provides an interaction with the transformation process that improves understanding of the observed effects. Once the setup is established subsequent activities will show how Fourier Transformation, often regarded as a mathematical tool, can be applied in dramatic ways to practical tasks in the physical world.

In the following pages, we will take a more careful look at the focal plane and image formation due to the experimental setup shown below.



https://www.repairfaq.org/sam/foiproc5.gif

Figure 7: Implementation of Fourier optical image processing

4.1.1 Examine Optical Noise

In the optical setup you'll use for demonstrating Fourier Transforms there are several sources of noise. The laser tube generates noise, often due to imperfection in the mirrors, bore, operational stability, dust particles captured during manufacture, etc. The noise shows up as stray light or undesired patterns around the main beam. Lenses in the setup are another source of optical noise. Dust and imperfections within the lens can cause unwanted interference patterns that have nothing to do with the object being tested. Basically, anywhere a coherent optical beam is generated, passes through an interface, or intercepts a target, is a potential source of the noise.

In order to satisfactorily examine the diffraction image of various objects, it will be necessary to reduce optical noise. This noise may be produced within the laser tube or may be caused by dust or imperfections on subsequent optical surfaces. Optica noise is sometimes visible as stray light around an unexpanded laser beam. To view this noise, I shined a laser beam on a white card placed about one meter away from the laser. If the room has been darkened, it is possible that the beam on the viewing screen will include a secondary beam produced by an internal reflection within the output mirror coatings; or dull blotches of light produced by internal reflections from the walls of the laser cavity.

Fortunately, there’s a fairly simple technique that will eliminate most of this noise. It involves using a spatial filter, which is essentially a pinhole through which the laser beam is focused to strip off many of these unwanted artifacts.

4.1.2 Spatial Filter and types

Spatial filtering is the most fundamental process in digital image processing. It involves the manipulation of digital images through the transformation and processing of pixels, or elements of a picture. Much like image formation, it employs a smoothing or sharpening filter to improve the quality of an image. The process of spatial filtering normally operates on a two-dimensional data array that represents an image.

We can observe how different spatial frequencies of the aforementioned diffraction pattern contribute to image formation. High-pass filters involve obstructing lower spatial frequencies located in the middle of the object's diffraction pattern in the Fourier plane. This kind of filtering results in the edge enhancement of an object. Edge enhancement can be used to easily locate and define the edges of fine objects. Low-pass filters block out higher spatial frequencies located at the edges of the diffraction pattern in the Fourier plane. Blocking out higher spatial frequencies leads to degradation of the image quality. All lenses are of finite size, so all image formation involves low-pass filtering to some degree, and all lenses contribute to image degradation of the original object. Low-pass spatial filtering can be used to filter out grain noise highlighted by higher spatial frequencies in photographic emulsions.

Amplitude spatial filtering is closely related to the more general field of Fourier optics, as well as optical imaging. There are two types of Amplitude spatial filtering; the Vertical-pass filter: Which blocks horizontal frequency and transmits vertical frequency and the Horizontal-pass filter which Blocks vertical frequency and transmits vertical frequency.

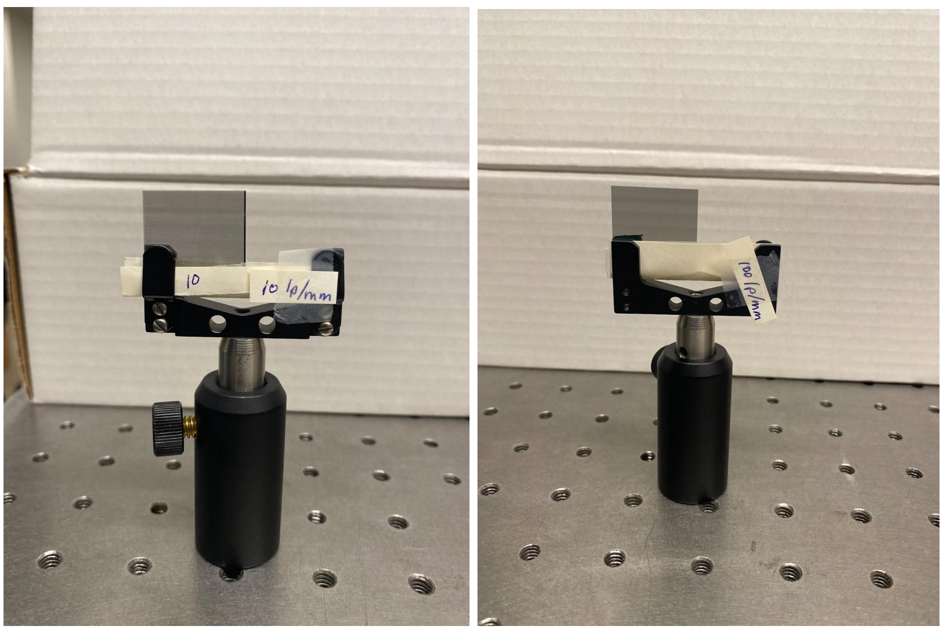


Figure 8: Vertical pass filter grating(left) and Horizontal pass filter (right)

Making a spatial filter

A spatial filter works by exploiting the fact that stray or off-axis light from a laser will focus at a different point in space than the desired main beam. The main components of a spatial filter are a focusing lens and pinhole as shown in the following figure:

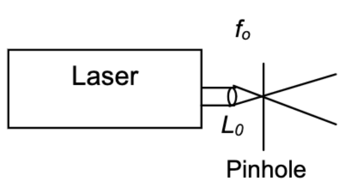


Figure 9:   Making Spatial filter

The lens focuses the laser beam to a pinpoint, and a pinhole is placed at the focal point of the lens. Optical energy from noise generated in the laser focuses at different locations than the main beam – basically in a larger concentric circle around the main beam at the focal point of the lens. By making the pinhole large enough to just pass the main beam the remaining optical noise energy is blocked. A spatially filtered laser beam generates a clean spot with uniform illumination when viewed on a flat white reflecting screen. Rings or other artifacts around the spot would indicate a pinhole that was too large or a misaligned setup.

Expand and Collimate the beam

Most of the subsequent exercises an object will be exposed to the laser beam to develop a diffraction pattern. To get the best results it's important that the beam is highly collimated, one whose rays are parallel and whose diameter remains constant over distance. A collimated beam behaves as if the light source was infinitely small (point source) and at an infinite distance from the observer.

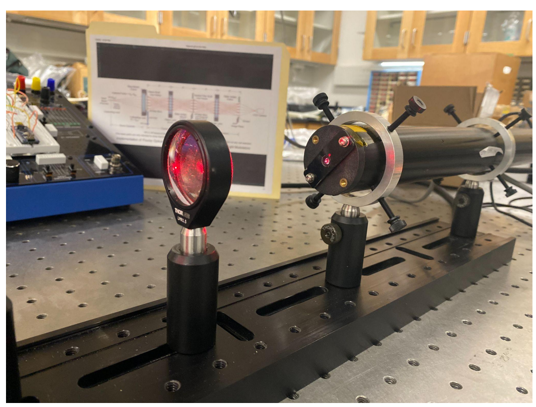


Figure 10: 633nm wavelength HeNe laser with Collimate lens

The beam coming out of the spatial filter is rapidly diverging which can be observed by looking at how the spot size increases at several distances. A collimated beam between 20 and 30 mm in diameter is needed to fully illuminate the photographic transparencies and other objects used in the exercises. We can develop this beam by placing a large diameter converging lens with a suitable focal length after the spatial filter.

Observing Diffraction Patterns

A collimated beam of coherent light is ideal for observing diffraction patterns. Using the laser and spatial filter setup developed and aligned earlier. I place solid objects and transparencies inside the collimated laser beam and view the diffraction patterns on a viewing screen.

A lens is usually used to create a pattern called Fraunhofer diffraction in its focal plane. (This is why a lens is sometimes referred to as a Fourier transform.) The back focal plane of the lens will then become the Fourier plane of the setup, and this is where the diffraction pattern or the Fourier transform of the object is located. Thus, in most cases, after the light passes the focus of this lens and its diffraction pattern is formed at the focus, it begins to again interfere to reform the image of the object.

Theoretically, however, the image is never truly focused if the object is located a focal length away from the lens, so a second lens is needed to bring what would be an infinite image distance to a particular, finite image plane. In other words, a second lens located a focal length away from the Fourier plane makes the infinitely far away image focus on the image plane. In the experimental setup, then, a second lens is located a third focal length away from the Fourier plane and performs an inverse Fourier transform on the diffraction pattern, forming an inverted image of the object in its back focal plane.

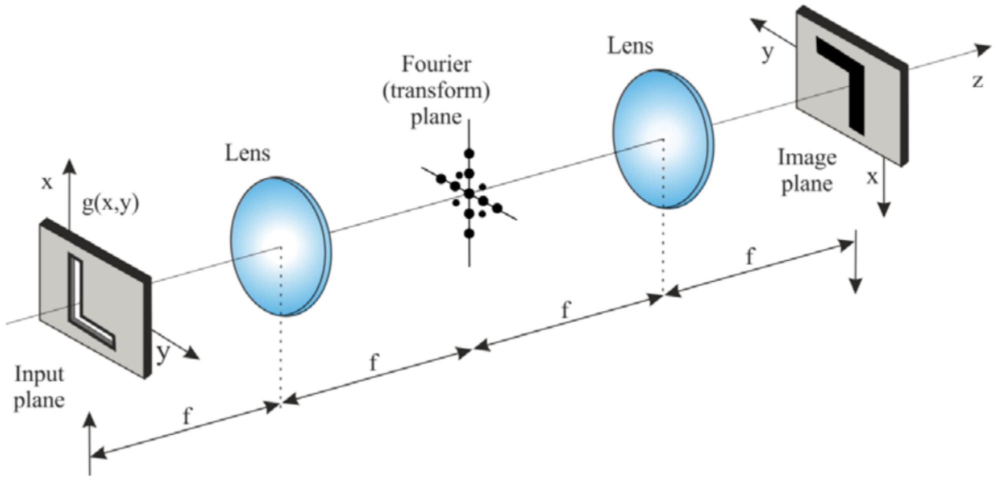


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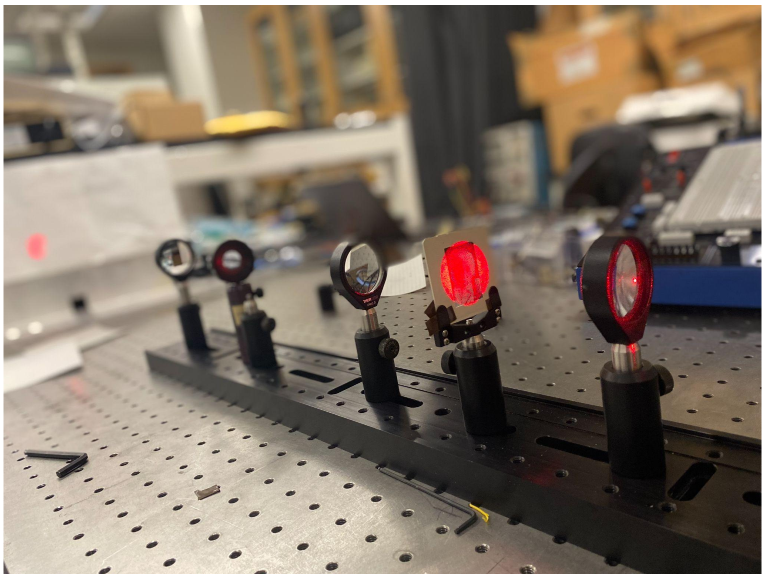
Figure 11: Two-dimensional optical spatial frequency processor

Note: Moreover what actually happens is double diffraction. The first lens (object lens) produces a diffraction pattern, the Fourier transform of an object. The second lens (image lens) produces a diffraction pattern derived from the first diffraction pattern. This second diffraction pattern functions as an inverse Fourier transform and pronounces an image of the original object.

Result and Discussion

As we discussed earlier when coherent light is diffracted and passed through a lens, the lens optically performs the transform function. The result is the formation of a diffraction image, the Fourier transforms which provides amplitude, phase, and position information concerning the original waveform.

Setup 1: No spatial filter or Fourier plane



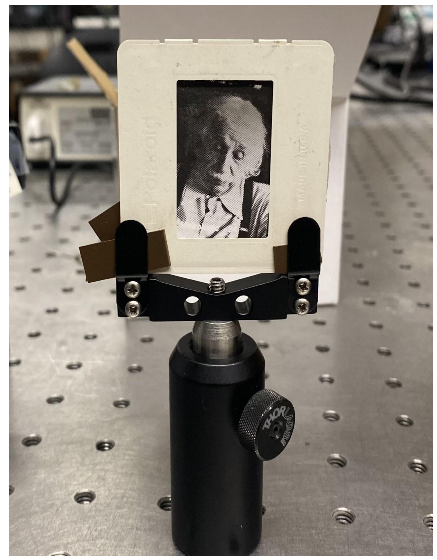
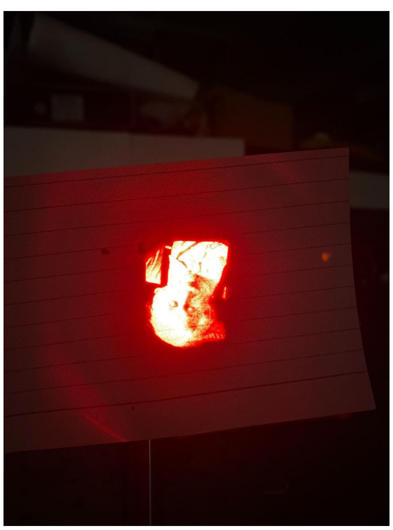


Figure 12: The image to the left shows the setup of our image without any spatial filter while the image to the right shows the transparent image we used throughout my experiment.



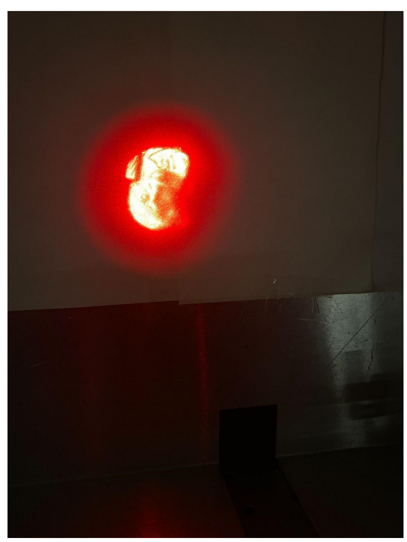


Figure 13. The image was taken on the image plane screen 2 focal lengths away (on the left) and 4 focal lengths away from the Fourier plane.

Setup 2: The image plane screen is placed on the Fourier transform plane

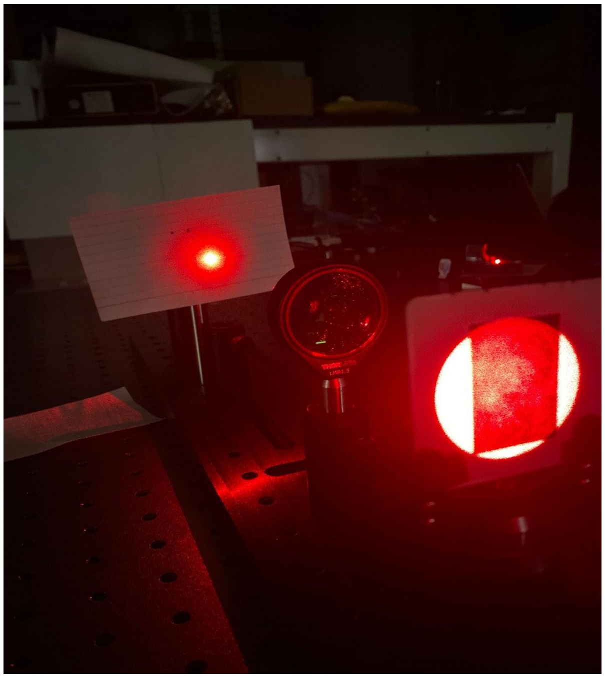


Figure 14: Shows the Fourier transform of Albert Einstein without any spatial filter.

The laser beam first goes through a lens with a short focal length. At the focus, a small aperture is placed. The light must come through the aperture. When an asymmetrical and bright pattern of rings appears after the light leaves the aperture, then the maximum light has passed and has been diffracted through the aperture. This pattern is called an Airy disk pattern (below) and is a diffraction pattern of a circular aperture. Thus, the aperture allows only the most collimated light going through the center of the first lens to focus at the aperture.

Setup 3: Vertical passing filter is placed after the image

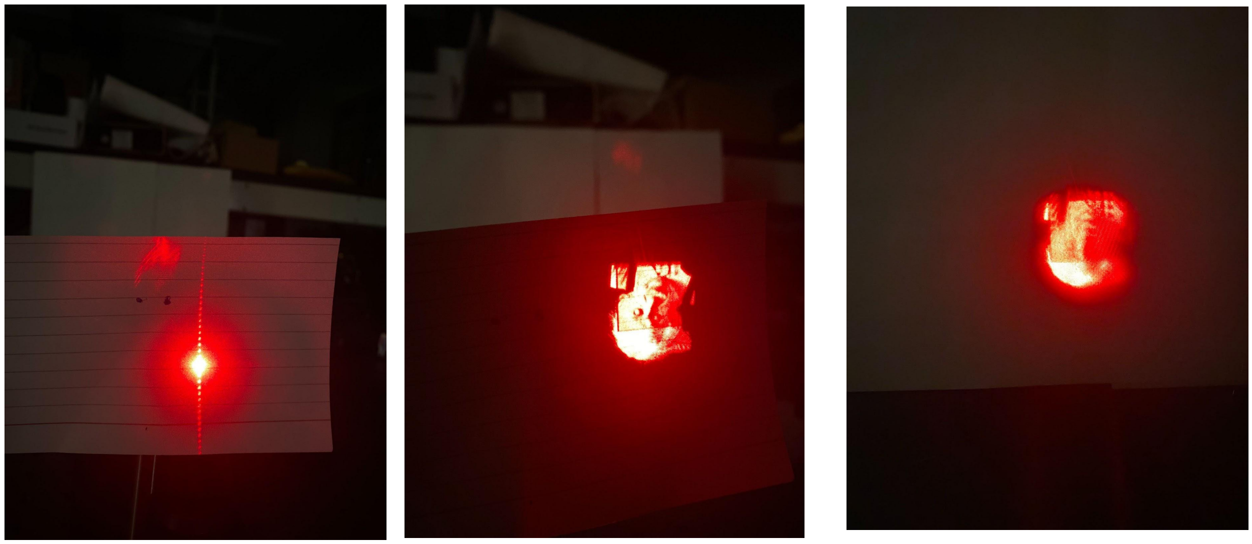


Figure 15: The first image shows the Fourier transform of Albert Einstein's image at the Fourier transform plane. The second and third images are taken on the image plane screen 2 focal lengths away (on the left) and 4 focal lengths away from the Fourier plane while a vertical passing filter is placed after the image.

Setup 4: Horizontal passing filter is placed after the image plane

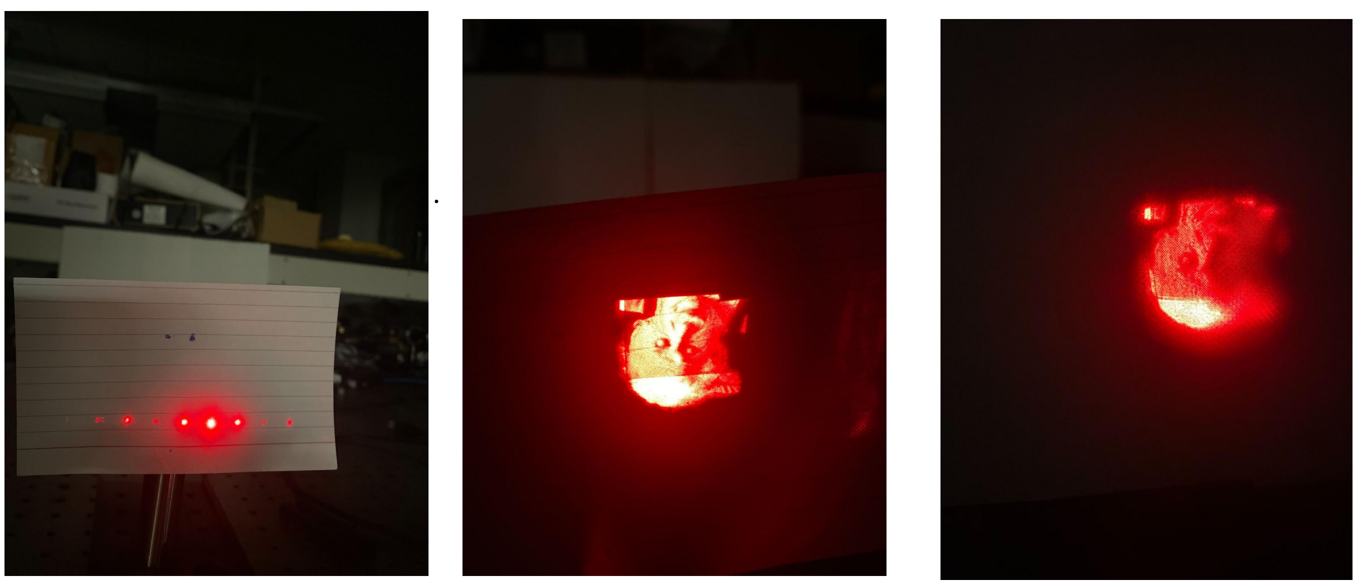


Figure 16: The first image shows the Fourier transform of Albert Einstein's image at the Fourier transform plane. The second and third images are taken on the image plane screen 2 focal lengths way (on the left) and 4 focal lengths away from the Fourier plane while a horizontal passing filter is placed after the image.

One analysis I did to confirm if the Fourier transform of Albert Einstein's image was using the first picture from setup 4, we can calculate the distance between the dot(bright spot) using the Ronchi ruling method. According to Huygens' Principle, the light that passes through these slits can be thought of as a new source. So now we have multiple sources of light, just as we had multiple sources of sound waves (speakers) in the superposition of the sound lab. The waves from these sources will interfere, sometimes constructively, sometimes destructively, yielding bright and dark spots respectively.

The centers of the bright spots should be at places of constructive interference, i.e. where the path difference is an integral multiple of the wavelength. After some analysis and approximations we are led to a relatively simple formula:

$$Ym \quad = \; m(\frac{\lambda f}{d})$$

where ym is the distance between the center spot and the mth bright spot from it, m is an integer (1, 2, 3 ...), λ is the wavelength of the light, L is the distance between the slit source and the screen where the spots are observed, and d is the distance between the slits.

Using Ronchi method the distance for the first three dots are:

	1st dot	2nd dot	3rd dot
Experimental	0.2518	0.7584	1.264
Theoretical	0.1921	0.5773	0.9606

Table 1: Experimental and theoretical result using Ronchi ruling method

Where $\lambda = 633nm$

$M = 1,2,3\ldots\ldots$

$b = 0.25mm$

This measurement has uncertainty of 0.05mm. From the above result, we can conclude that our result approximately matches our theoretical result which in extends means we have a close Fourier transformation of the Albert Enstian image.

Note: The narrower the spacing between the lines, the greater the distance between the diffraction dots. The diffraction pattern sketches for the transparencies should resemble the first image from setups 3 and 4.

In general, **t**he results from above make it clear that high spatial frequencies form the edges of the image of an object, and the low spatial frequencies form the general outline of the object. Many applications exist for both kinds of filtering. Low spatial filtering can be used to filter out grain noise from photographs caused by high spatial frequencies. High spatial filtering is useful when measuring the profile of an object or optically observing irregularities in the contour. Also, amplitude filtering performed here can be combined with phase filters in complex filtering. This kind of filtering can lead to pattern recognition and incorporates the ideas of holographic optical processing.

Conclusion

Given my project objectives we feel that the opportunity to work on this endeavor greatly enhanced our appreciation and awareness of the resources and technologies that I take for granted daily. The intent of this experiment was to provide a practical perspective on Fourier Transformation. Taking part in this project, I have learned a great deal about Fourier optics and information and signal processing concepts and gained a more intuitive understanding of the transformation process. Hopefully, the experience gained working on this project will affect my future in regards to optics-based advancing technologies that would benefit the most underprivileged in our communities and societies. An example would be advanced image processing software applications available to manipulate digital camera images, like Adobe Photoshop. One to remember is that regardless of whether the manipulations are done using computer algorithms on digital data, or with analog techniques, the fundamental principles are the same.

Further Work

While the demonstration of Fourier optics can be done using only a laser, some lenses, and spatial masks made from pieces of tape, wires, etc., being able to input images and filters digitally would be highly desirable. It appears to be possible to modify a common 1.3 inch 240x240 pixel LCD to act as a full-color Spatial Light Modulator (SLM). LCD is a flat-panel display electronically modulated optical device that uses the light-modulating properties of liquid crystals combined with polarizers. These LCDs are easily driven from an Arduino-compatible microprocessor board like the Atmega 328 Nano 3.0. There are Arduino libraries to drive them as well as demo programs to get you started. The LCDs are listed as something along the lines of: "1.3 Inch Color IPS TFT LCD Display SPI ST7789".

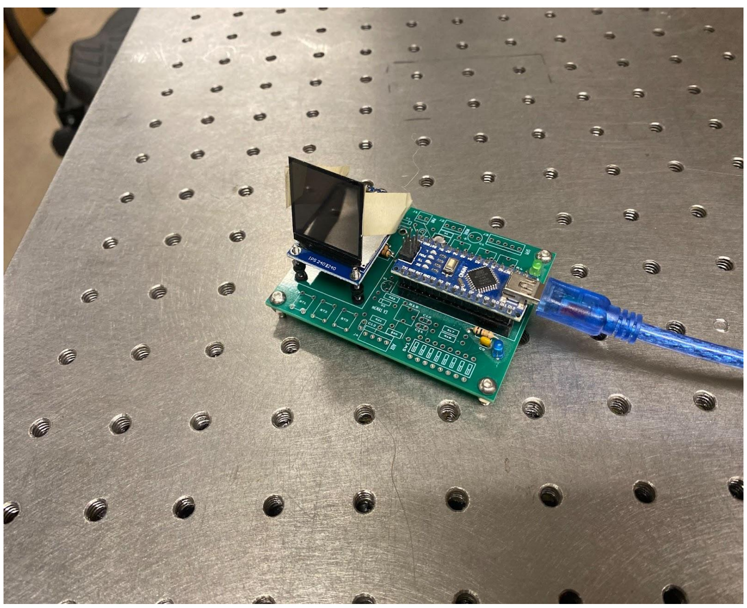


Fig. A liquid-crystal display (LCD)

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